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14. ABSTRACT
In 2008, two major category 2 hurricanes impacted the northern Gulf of Mexico. Hurricane Gustav made a landfall near Cocodrie, Louisiana on September 1, and Hurricane Ike at Galveston, Texas on September 13. Both surface and subsurface changes of sea states caused by these hurricanes were captured by remote sensing. Measurements of sea surface temperature (SST) from MODIS and chlorophyll a (Chla) concentration from SeaWiFS after Gustav and Ike showed evidence of upper-ocean cooling along their tracks and, subsequently, an increase in Chla concentration that is normally not present in the oligotrophic waters of the Gulf of Mexico. In particular, phytoplankton blooms were observed by SeaWiFS in the south of Atchafalaya Bay after Gustav and in the Louisiana Bight west of Mississippi bird-foot delta after Ike. Ike caused large-scale flooding east of Galveston, and plumes of high Chla region near river outlets of western Louisiana coast appeared in SeaWiFS data a few weeks later. Moreover, cloud-free weather in late September afforded true-color imagery from MODIS showing estuarine discharge plumes, sediment transport, and shelf eddies along the Louisiana and Texas coast. These important surface/subsurface phenomena triggered by the hurricanes cannot be understood by remote sensing alone. The high-resolution (~~2km) Navy Coastal Ocean Model (NCOM) developed for Mississippi-Louisiana-Texas (MsLaTex) coast provided additional information, such as sea surface height, degree of vertical stratification, and 3D ocean current vectors, to examine the coastal water responses to hurricanes.

15. SUBJECT TERMS
sea surface temperature, MODIS, Louisiana Bight, Gulf of Mexico

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Satellite Observations and NCOM Assessment of the Mississippi-Louisiana-Texas Coast following Hurricanes Gustav and Ike

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***Abstract*—In 2008, two major category 2 hurricanes impacted the northern Gulf of Mexico. Hurricane Gustav made a landfall near Cocodrie, Louisiana on September 1, and Hurricane Ike at Galveston, Texas on September 13. Both surface and subsurface changes of sea states caused by these hurricanes were captured by remote sensing. Measurements of sea surface temperature (SST) from MODIS and chlorophyll a (Chla) concentration from SeaWiFS after Gustav and Ike showed evidence of upper-ocean cooling along their tracks and, subsequently, an increase in Chla concentration that is normally not present in the oligotrophic waters of the Gulf of Mexico. In particular, phytoplankton blooms were observed by SeaWIFS in the south of Atchafalaya Bay after Gustav and in the Louisiana Bight west of Mississippi bird-foot delta after Ike. Ike caused large-scale flooding east of Galveston, and plumes of high Chla region near river outlets of western Louisiana coast appeared in SeaWiFS data a few weeks later. Moreover, cloud-free weather in late September afforded true-color imagery from MODIS showing estuarine discharge plumes, sediment transport, and shelf eddies along the Louisiana and Texas coast. These important surface/subsurface phenomena triggered by the hurricanes cannot be understood by remote sensing alone. The high-resolution (~2km) Navy Coastal Ocean Model (NCOM) developed for Mississippi-Louisiana-Texas (MsLaTex) coast provided additional information, such as sea surface height, degree of vertical stratification, and 3D ocean current vectors, to examine the coastal water responses to hurricanes. We use NCOM to explain physical conditions that caused the plankton blooms and other unusual shelf dynamics after hurricanes Gustav and Ike in the northern Gulf of Mexico.**

I. Introduction

Hurricanes Gustav and Ike were the two major hurricanes that affected Mississippi-Louisiana-Texas (MsLaTeX) coast in the northern Gulf of Mexico during summer 2008. Gustav entered the Gulf of Mexico on August 31 as a Category 4 hurricane. It weakened but grew in size as it crossed the Gulf and made a landfall near Cocodrie in the west of Terrebonne Bay, Louisiana, around 1500 UTC on Septermber 1 with maximum winds near 90 kt (46.30 m/s, Category 2). Ike was a Category 1 hurricane when it entered the Gulf of Mexico on September 10 but intensified as it moved slowly northwestward over the southeastern Gulf and landed Galveston Island on September 13 as a strong Category 2 hurricane with maximum wind of 95 kt (48.87 m/s). Its large size brought storm surge of over 12 feet (3.7 m) from Galveston Island eastward into southern Louisiana. Comprehensive information of both hurricanes are found in National Hurricane Center's Tropical Cyclone Reports (www.nhc.noaa.gov/2008atlan.shtml).

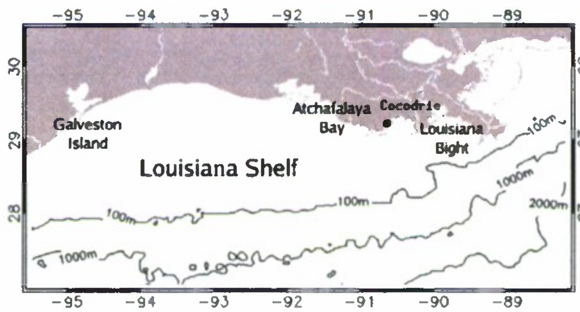

Fig. 1. MsLaTex coast.

The MsLaTex coast (Fig. 1) is characterized by a narrow continental shelf in the west of Mississippi bird-foot delta and the world's 7th largest fresh water discharge from Mississippi-Atchafalaya River system. The high influx of nutrient-rich water contributes to significant biological productivity, and excessive amount of living organisms could deplete oxygen in this region (hypoxia). The fresh water discharge may also cause strong stratification, cutting off the oxygen supplies in the bottom water. In fact, the Louisiana continental shelf is known as the second largest zone of coastal hypoxia in the world [1].

Hurricanes impact the northern Gulf of Mexico in many different ways. Their severe winds can cause disastrous damage to the economy and ecosystem of coastal communities, but they also redistribute material in coastal water derivered from the continental interier, revitalizing the region susceptible to hypoxia [2]. We investigate the effect of hurricanes Gustav

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and Ike from this perspective. Although many studies on how hurricanes impact deeper oceans exist ([3]–[6]), our emphasis is to understand shallow-water response to hurricanes in the continental shelf of MsLaTex coast using remote sensing and numerical modeling.

II. Methods

A. Satellite Data

Remote sensing data were obtained from NASA's Ocean-Color website (oceancolor.gsfc.nasa.gov). We downloaded Level-2 sea surface temperature (SST) product from MODIS and Level-1 chlorophyll a (Chla) product from SeaWiFS. The Level-1 Chla data from SeaWiFS were further processed into Level-2 using SeaDAS software developed by NASA's Ocean Color group. For aerosol calculation, we used multi-scattering with 2-band model selection mode (NIR correction is not included) particularly suited for the region. Pixels with excessive cloud cover or stray light, large solar zenith angles ($> 75\,^{\circ}$), large sensor zenith angles ($> 60\,^{\circ}$), or total radiance greater than the knee value, were masked out. The Level-2 SST data from MODIS were binned into Level-3 at 1km resolution in order to calculate 5-day average. True-color images were generated from Level-0 MODIS-Aqua files using the standard algorithm in SeaDAS.

B. Numerical Model

The high-resolution (~2km) Navy Coastal Ocean Model (NCOM) is nested within the Intra-Americas Sea regional model at Naval Research Laboratory (NRL IASNFS) [7]. IASNFS provides sea level variation, 3D ocean currents, temperature and salinity for the open boundary conditions. Model topography is based on the NRL DBDB2 and the NGDC hydrographic data with a domain that includes both shallow and deep waters. The model is driven by wind, heat fluxes, solar radiation, and air pressure and assimilates satellite altimeter data and MODIS SST. The data assimilation and forcing are described in Ko et.al. [8]. Animation of NCOM results used in this study is available at gulf-coast.lsu.edu/CoastModel2008.html.

III. Results and Discussion

A. Gustav

1) Phytoplankton bloom off the Atchafalaya Bay: Fig. 2 shows a 5-day averaged map of Chla concentration measured by SeaWiFS in the eastern coast of Louisiana after the passage of Gustav. An arrow-shaped area of high concentration around ~(28.1N, 91.5W) indicates the occurrence of a phytoplankton bloom. The difference between 5-day average maps of SeaWiFS Chla concentration before and after Gustav was as large as 4.725 $mg\,m^{-3}$ inside the bloom. Plankton blooms in satellite imageries are frequently observed after hurricanes, and studies in the past found that vertical mixing and upwelling of cooler and nutrient-rich water induced by a hurricane are the primary cause of increased biological production [3], [4]. The 5-day average maps of SST from MODIS after Gustav and Ike showed evidence of surface cooling along their tracks, in accordance with those studies. It is also known that blooms after hurricanes often occur in the pre-existing sites of a cold-core eddy, since its counter-clockwise circulation is enhanced by hurricane wind, and divergence at the center of a cold-core eddy brings deeper, nutrient-rich water toward the surface [4]. Most recently, Chla enhancements in the site of cold eddies along the paths of hurricanes Katrina, Rita and Wilma in 2005 were reported [5], [9]. Fundamental mechanisms for the bloom in Fig. 2 are probably different from such examples since location of the bloom is too close to the shore for typical mesoscale eddies.

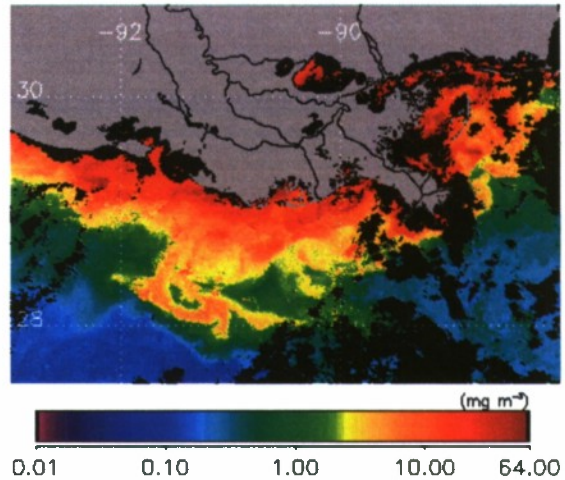

Fig. 2. 5-day averaged map of Level-2 Chlorophyll a concentration data from SeaWiFS after Gustav (Sep 2-6). Elevated concentration of chlorophyll a are observed at ~(28.1N, 91.5W).

NCOM salinity prediction during Hurricane Gustav indicated a significant amount of fresh water flow into the Atchafalaya shelf near the sea surface. It was driven by pre-existing offshore eddies, as evidenced in NCOM sea surface height. The cross-shelf flow of fresh water through a channel formed by a cyclonic/anti-cyclonic eddy pair is a recurrent process in this region during summer [10]. The 5-day averaged Chla map from SeaWiFS between August 26 and 30 shown in Fig. 3 support the existence of such circulation pattern prior to Gustav in the northern Gulf of Mexico. This movement of upper water away from the coast would have caused water in the bottom to rise over the shelf slope, prompting an upwelling in nearshore waters. Furthermore, sea surface height predictions from NCOM suggested a strong setup and setdown of sea level west of Cocodrie that may result in strong vertical mixing of water column off the Achafalaya Bay. The redistribution of nutrient-rich water may lead to increase in Chla concentration observed in Fig. 2.

2) Vertical mixing: The surface cooling observed by MODIS was more intense after Ike than after Gustav, likely because Gustav elevated the thermocline in the Gulf in advance to Ike. Vertical profile of NCOM salinity at the bloom location in Fig. 2 showed a maximum at 70m depth prior to Gustav. After Gustav's passage, salinity decreased both at surface and

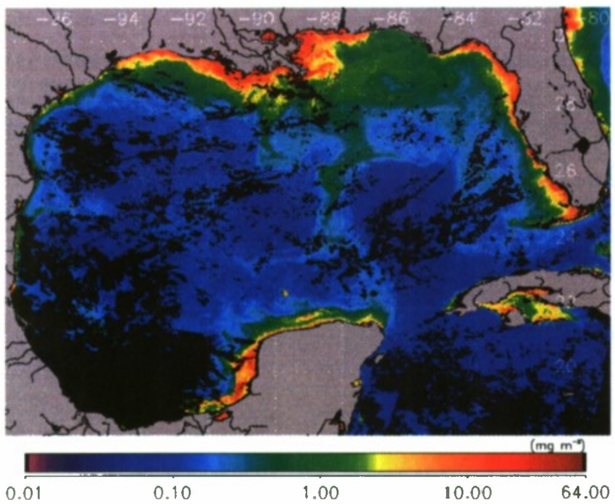

Fig. 3. 5-day averaged map of Chlorophyll a concentration from SeaWiFS before Gustav (Aug 26-30) indicates cross-shelf transport of Chla driven by offshore eddies.

at -70m, suggesting that nutrients may came in to the mixed layer from both above and below. Location of the bloom ($\sim$28.1N) in Fig. 2 corresponds to the shelf edge where effect of shear stress is most intense [11]. The sudden change in temperature caused by Gustav was visible all the way down to 200m depth along the shelf edge in NCOM prediction. Strong vertical mixing combined with upwelling provide a mechanism for the enhancement of Chla at the shelf edge.

B. Ike

1) Enhancement of Chla concentration along LaTeX coast: Fig. 4 shows Chla data from SeaWiFS a few weeks after the passage of Ike. Initially, Ike's effect on Chla concentration was seen to be limited mainly to the nearshore waters along the Louisiana coast. Ike caused large-scale flooding east of Galveston. Discharge of these ponded waters, rich in nutrient, likely enhanced Chla concentration near Galveston as shown in Fig. 4 of September 30. The effect of Ike was also visible in a true-color imagery from MODIS-Aqua on September 28 (Fig. 5). It shows notable amount of plumes from Mississippi bird-foot delta and Achafalaya river, Calcasieu and Sabine Lakes in the southwest Louisiana, and Galveston Bay in Texas. Green water in the Louisiana shelf signifies the increased biological activity in the region. Dark green water in the south of Louisiana Bight indicates an outward flow of Chla through a channel, in agreement with the NCOM prediction mentioned in Section A.

2) Phytoplankton bloom in Louisiana Bight: Fig. 4 also shows a plankton bloom in the Louisiana Bight on September 25 west of the bird-foot delta. NCOM ocean current prediction suggests that formation of a clockwise gyre after Ike at the south of Louisiana Bight may have played a role. The clockwise gyre is a persistent feature of the region which exists 70% of the time [10]. Westward current passing around the sharp corner of Mississippi bird-foot delta tends to form a gyre as it exits to the Louisiana Bight. This clockwise gyre may block offshore transport of nutrient-rich water, allowing phytoplankton to accumulate inside the Louisiana Bight.

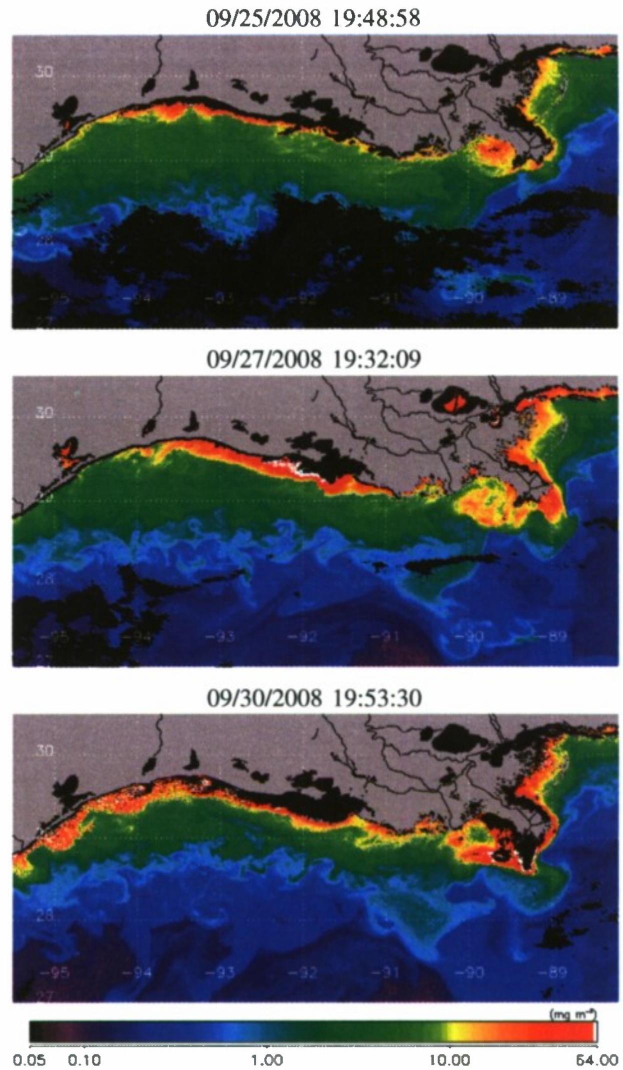

Fig. 4. Chlorophyll a concentration measured by SeaWiFS after Ike.

3) Formation of eddies on the Louisiana shelf: Numerous shelf eddies found in Fig. 5 are likely due to a jet stream induced by Ike. Such an inflowing jet along the shelf edge causes water to spiral out on a horizontal plane along its propagating path, as demonstrated in Thiem et. al. [12].

IV. Conclusion

We investigated the coastal ocean response to hurricanes Gustav and Ike at the northern Gulf of Mexico using satellite data and NCOM prediction. The NCOM prediction during Hurricane Gustav indicated upwelling favorable condition on the Atchafalaya shelf, followed by strong vertical mixing along the shelf edge. The plankton bloom observed by SeaWiFS on September 5 is likely a result of such mechanisms. Investi-

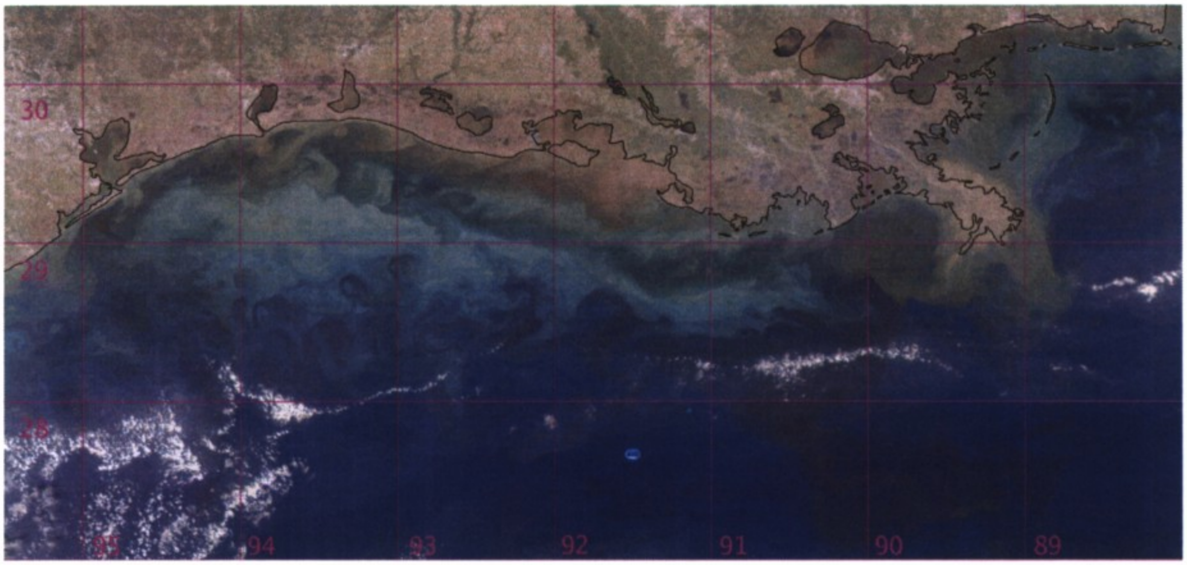

Fig. 5. True-color image from MODIS-Aqua satellite on September 28 (19:35:00 UTC) shows estuarine discharge plumes, sediment transports, and shelf eddies in the wetern region hit by Ike.

gation applying satellite data and NCOM prediction during Hurricane Ike showed the impact of hurricane on the evolution of Chla along the MsLaTex coast. Shelf eddies captured by MODIS-Aqua truecolor imagery are likely due to a jet stream of current at the edge of Louisiana Shelf induced by Ike. Cooling of ocean temperature by Gustav provided a favorable condition for a strong cooling and an extended Chla enhancement by Ike.

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